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Reducing herbicide runoff from agricultural fields with vegetative filter strips: a review

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Although the effectiveness of vegetative filter strips (VFS) for reducing herbicide runoff is well documented, a comprehensive review of the literature does not exist. The objectives of this article are to denote the methods developed for evaluating herbicide retention in VFS; ascertain the efficacy of VFS regarding abating herbicide runoff; identify parameters that affect herbicide retention in VFS; review the environmental fate of herbicides retained by VFS; and identify future research needs. The retention of herbicide runoff by VFS has been evaluated in natural rainfall, simulated rainfall, and simulated run-on experiments. Parameters affecting herbicide retention in VFS include width of VFS, area ratio, species established in the VFS, time after establishment of the VFS, antecedent moisture content, nominal herbicide inflow concentration, and herbicide properties. Generally, subsequent transport of herbicides retained by VFS is reduced relative to adjacent cultivated soil because of enhanced sorption and degradation in the former.

Key words: Adsorption, buffer strip, degradation, infiltration, leaching, microbial activity, sedimentation, simulated rainfall, simulated run-on.

Agricultural runoff is the primary mechanism contributing to herbicide contamination of surface water. Herbicide runoff is defined as dissolved and sediment-adsorbed herbicides transported by water from a treated land surface (Leonard 1990). Unless severe rainfall occurs within 2 wk after application, herbicide losses are typically < 0.5% of the amounts applied (Wauchope 1978). In 1997, herbicide applications in the United States exceeded 1.8×10^8 kg ai (Gianessi and Marcelli 2000), with potential off-target losses exceeding 9.1×10^5 kg.

Herbicide-monitoring studies have confirmed contamination of reservoirs (Thurman et al. 1996), lakes (Senseman et al. 1997; Thurman et al. 2000), streams (Scribner et al. 2000; Senseman et al. 1997), and rivers (Clark and Goolsby 2000; Senseman et al. 1997; Thurman et al. 1996). The most commonly detected herbicides include metolachlor, atrazine, simazine, cyanazine, and alachlor (Clark and Goolsby 2000; Scribner et al. 2000; Senseman et al. 1997; Thurman et al. 1996, 2000). The presence of these herbicides in surface water presents a potential health risk because they are listed as either probable or possible human carcinogens (Nowell and Resek 1994).

Vegetative filter strips (VFS) are a best management practice (BMP) recommended by the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) for reducing nonpoint source pollution. VFS are defined as areas planted to grass or other vegetation along the perimeter of cropland to reduce sediment and chemical transport from agricultural fields (Christensen et al. 1993). VFS serve a number of functions related to reducing herbicide runoff including (1) decreasing runoff transport capacity, which facilitates deposition of sediment-adsorbed herbicides (Arora et al. 1996; Asmussen et al. 1977; Barfield et al. 1998; Hall et al. 1983; Patty et al. 1997; Rankins et al. 2001; Tingle et al. 1998), (2) enhancing infiltration compared with the source area (Arora et al. 1996; Asmussen et al. 1977; Barfield et al. 1998; Hall et al. 1983; Kloppel et al. 1997; Lowrance et al. 1997; Mersie et al. 1999b; Misra et al. 1996; Patty et al. 1997; Rankins et al. 2001; Rhode et al. 1980; Schmitt et al. 1999; Seybold et al. 2001; Tingle et al. 1998; Vellidis et al. 2002), (3) sorbing dissolved-phase herbicides to the grass, grass thatch, or soil surface (or all) (Arora et al. 1996; Asmussen et al. 1977; Barfield et al. 1998; Krutz et al. 2003a, 2004b; Lowrance et al. 1997; Misra et al. 1996; Patty et al. 1997; Rhode et al. 1980; Seybold et al. 2001; Vellidis et al. 2002), and (4) behaving as a herbicide sink where irreversible sorption, microbial degradation, and plant uptake are enhanced (Benoit et al. 1999; Blanche et al. 2003; Krutz et al. 2003b, 2004a; Mersie et al. 1999b; Paterson and Schnoor 1992; Rankins et al. 2002; Seybold et al. 2001; Staddon et al. 2001).

Although the effectiveness of VFS for reducing herbicide runoff has been evaluated for over 25 yr, a comprehensive review of the literature does not exist. The objectives of this article are to identify the advantages and disadvantages of natural rainfall, simulated rainfall, and simulated run-on studies; determine the efficacy of VFS as a function of width, area ratio, type of vegetation established in the filter strip, time after establishment of the VFS, antecedent moisture content, nominal herbicide inflow concentration, and herbicide properties; evaluate the environmental fate of herbicides once retained by vegetated filter strips including adsorption–desorption, degradation, plant uptake, and leaching; and identify future research needs.

Methods for Studying Herbicide Retention in Vegetative Filter Strips

The effectiveness of VFS in mitigating herbicide transport from application zones is quantified through one of two approaches. In the first approach, herbicide runoff from the source area flows across the VFS where runoff volume, sediment load, and herbicide concentration are determined solely at the VFS outflow. The effectiveness of the VFS treatment is determined by comparing runoff volume, concentration changes, or reductions in mass load (or all) with a control plot void of a VFS (Patty et al. 1997; Rankins et al. 2001; Rhode et al. 1980; Tingle et al. 1998; Webster and Shaw 1996). Because inflow data are not collected, it is not possible to partition herbicide trapping efficiency among known retention mechanisms including sedimentation, infiltration, and sorption. Thus, these experiments are ineffective for elucidating the mechanisms contributing to herbicide retention in the VFS. In the second approach, herbicide runoff from the source area is directed onto the VFS where runoff volume, sediment load, and herbicide concentration are determined at both the VFS inflow and the VFS outflow. The design allows calculation of a mass balance whereby trapping efficiency may be partitioned among sedimentation, infiltration, and sorption. This approach can be divided into experiments whereby the VFS does or does not intercept rainfall.

In experiments where the VFS intercepts rainfall, herbicide concentration changes associated with dilution are quantified with one of two methods. In the first method, a conservative tracer, typically potassium bromide (KBr), is used and dilution factors are calculated from the fractional changes in concentration of bromide as the water passes through the VFS (see Misra et al. 1996; Schmitt et al. 1999; Vellidis et al. 2002). The method assumes that rainfall is devoid of bromide and that changes in the concentration of bromide are due solely to dilution (i.e., the negatively charged bromide ion is neither absorbed or adsorbed by the vegetation nor sorbed to the VFS grass, grass thatch, or soil surface, or all). This method also accounts for dilution associated with throughfall seepage (i.e., reemergent shallow subsurface flow). The second method for quantifying dilution effects is based on the construction of a dilution factor, which accounts for the runoff entering the VFS and the rainfall intercepted by the VFS (Arora et al. 1996; Boyd et al. 2003; Lowrance et al. 1997). This method assumes that dilution associated with throughfall seepage is negligible.

In experiments where VFS do not intercept rainfall, researchers bypass the effect of rainfall dilution and assume that dilution associated with throughfall seepage and/or residual water associated with the VFS grass, grass thatch, and soil surface is negligible (Arora et al. 2003; Asmussen et al. 1977; Barfield et al. 1998; Krutz et al. 2003a, 2004b; Mersie et al. 1999b; Seybold et al. 2001). When these assumptions are valid, a mass balance is constructed whereby trapping efficiency may be partitioned between infiltration and sorption.

Natural Rainfall

In natural rainfall studies, herbicide is applied to the source area at recommended rates whereby the generation of runoff depends on natural rainfall events. The scale of natural rainfall studies is generally larger than other studies with reported plot sizes ranging from 40 m^2 to 2.5 ha (Arora et al. 1996; Hall et al. 1983; Lowrance et al. 1997; Patty et al. 1997; Rankins et al. 2001; Tingle et al. 1998; Vellidis et al. 2002; Webster and Shaw 1996). Natural rainfall studies have been used to compare the transport of herbicides from plots with and without VFS (Hall et al. 1983; Patty et al. 1997; Tingle et al. 1998; Webster and Shaw 1996) and to determine the efficacy of VFS as a function of in-field BMP (Hall et al. 1983; Webster and Shaw 1996), width of VFS (Patty et al. 1997; Tingle et al. 1998), type of vegetation established in the VFS (Lowrance et al. 1997; Rankins et al. 2001; Vellidis et al. 2002), leaching of herbicides beneath the VFS (Benoit et al. 2000; Lowrance et al. 1997; Vellidis et al. 2002), and herbicide properties (Patty et al. 1997; Rankins et al. 2001; Tingle et al. 1998; Vellidis et al. 2002).

The major limitation of natural rainfall studies is the inability to control crucial climatic variables (i.e., rainfall–runoff timing, rainfall intensity, rainfall duration). Consequently, in years when rainfall is inadequate to produce runoff during a time appropriate period, experiments result in little or no usable data. Depending on plot size, inadequate or untimely rainfall events (or both) may be augmented with simulated rainfall (Patty et al. 1997; Rankins et al. 2001; Tingle et al. 1998; Webster and Shaw 1996). Other limitations include the inability to control properties of the source area (i.e., surface crusting, compaction, water content), VFS (i.e., vegetation type, density, vigor, and stage of development), and runoff characteristics (i.e., volume, intensity, sheet vs. channel flow, herbicide concentration, herbicide load). Hence, data generated from natural rainfall experiments are often difficult to extrapolate to other field scenarios (Wauchope et al. 1995). However, because these experiments can be conducted at the watershed scale, it is likely that natural rainfall experiments result in the most realistic values for VFS efficacy.

Simulated Rainfall

In simulated rainfall experiments, herbicide is applied to the source area at recommended rates, and runoff is generated using rainfall simulators. Because of limitations imposed by the physical dimensions of the rain simulator, plots for simulated rainfall experiments are typically smaller than those for natural rainfall experiments and range in size from 28 to 125 m^2 (Asmussen et al. 1977; Barfield et al. 1998; Patty et al. 1997; Rankins et al. 2001; Rhode et al. 1980; Tingle et al. 1998; Webster and Shaw 1996). Simulated rainfall intensities are often based on worse case scenarios, 10 to 100 yr storm events, with intensities reported in the literature ranging from 1.9 to 25.4 cm hr^{-1} (Asmussen et al. 1977; Barfield et al. 1998; Patty et al. 1997; Rankins et al. 2001; Rhode et al. 1980; Tingle et al. 1998; Webster and Shaw 1996). Simulated rainfall experiments have been designed to compare the transport of herbicides from plots with and without VFS (Patty et al. 1997; Tingle et al. 1998; Webster and Shaw 1996) and to determine the efficacy of VFS as a function of in-field BMP (Webster and Shaw 1996), width of VFS (Barfield et al. 1998; Patty et al. 1997; Tingle et al. 1998), type of vegetation established in the VFS (Rankins et al. 2001), antecedent soil moisture level (Asmussen et al. 1977; Rhode et al. 1980), and herbicide properties (Patty et al. 1997; Rankins et al. 2001; Tingle et al. 1998).

The advantage of simulated rainfall experiments is the ability to control climatic variables (i.e., rainfall timing, intensity, and duration). Because simulated rainfall experiments are conducted at a smaller scale, researchers have greater control over source area parameters (i.e., soil texture, organic matter [OM] content, surface crusting, compaction, water content, slope), VFS parameters (i.e., vegetation type, vegetation density, soil texture, OM content, etc.), and runoff characteristics (sheet vs. channel flow). Consequently, simulated rainfall data are generally less variable and easier to interpret compared with data generated from natural rainfall experiments. However, because the plots of simulated rainfall experiments are restricted in size, data generated from these experiments must be extrapolated to the watershed scale; therein lies the limitation of simulated rainfall experiments, for they do not always emulate processes that occur at the watershed scale (i.e., sheet flow vs. channel flow, heterogenous soil texture and OM content, variable rain and duration, etc).

Simulated Run-on

Two types of simulated run-on studies are reported in the literature. In the first approach, herbicide is applied to the source area whereby runoff generated from natural rainfall events is captured in a distribution tank (Arora et al. 1996; Boyd et al. 2003). The captured runoff is subsequently delivered to the up-slope end of the VFS at a controlled rate. In the second approach, herbicide run-on is supplied from a nurse tank and applied to the up-slope end of the VFS at a known rate and herbicide concentration (Arora et al. 2003; Kloppel et al. 1997; Krutz et al. 2003a, 2004b; Mersie et al. 1999b; Mickelson et al. 2003; Schmitt et al. 1999; Seybold et al. 2001).

Relative to natural rainfall experiments, simulated run-on plots are typically smaller, ranging in size from 1.8 to 1,200 m^2, with the majority ≤ 3 m^2. Because simulated run-on experiments are conducted at scales similar to or slightly smaller than simulated rainfall experiments, the advantages and limitations of these methods are similar. However, several parameters that are difficult to control in natural rainfall and simulated rainfall experiments are controllable in simulated run-on experiments including run-on intensity (Arora et al. 1996, 2003; Boyd et al. 2003; Kloppel et al. 1997), nominal inflow herbicide concentration (Kloppel et al. 1997; Misra et al. 1996), and preferential retention of herbicides transported in the dissolved phase (Krutz et al. 2003a, 2004b; Misra et al. 1996). Because one has greater control over experimental variables in simulated run-on experiments, they may be better suited for VFS model development, whereas natural rainfall and simulated rainfall experiments serve for in situ model verification.

Variables Evaluated

The nomenclature and relevant chemical properties of the herbicides and vegetation reviewed are listed in Tables 1 and 2, respectively. A summary of the parameters influencing the retention of herbicides in VFS is given in Table 3. Table 4 contains species evaluated for the ability to enhance herbicide degradation in soil and a summary of the environmental fate of herbicides once retained in VFS is presented in Table 5. From the standpoint of herbicide transport and fate, the review is exhaustive. In an attempt to fill in research gaps, we have incorporated literature describing the fate and transport of metals, nutrients, and insecticides. For ease of discussion, variables affecting the retention of herbicide runoff are divided into three categories including filter strip properties, herbicide properties, and environmental fate. Subsequently, each category is subdivided into the specific variables that have been reported in the literature.

Regarding sedimentation and infiltration, the authors assume that strongly sorbed compounds with organic carbon partitioning coefficients (K_{oc}) $> 10^4$ ml g^{-1} and water solubilities < 1 μg ml^{-1} are transported almost entirely in the sediment phase (Wauchope et al. 1978). Consequently, variables increasing sedimentation are assumed to increase the retention of strongly sorbed herbicides. This distinction is in contrast to moderately sorbed herbicides with K_{oc} values $< 10^4$ ml g^{-1} and water solubilities > 10 μg ml^{-1}. Moderately sorbed herbicides have a higher sediment concentration than aqueous concentration; however, the proportion of sediment lost in a runoff event is considerably less than the amount of water lost through surface runoff. Thus, greater amounts of moderately sorbed herbicides are transported from the source area in the dissolved phase compared with the sorbed phase (Baker and Laflen 1979). As a result, variables that increase the infiltration capacity of the VFS are assumed to increase the retention of moderately sorbed herbicides.

Similar assumptions must be made regarding retention of moderately adsorbed herbicides by a sorption mechanism. Reduced concentrations of herbicide at the VFS outflow compared with the VFS inflow have been attributed to both sorption to the grass thatch–soil surface and dilution. Difficulties in separating concentration reductions between sorption and dilution are a common theme in the literature. Dilution resulting from rainwater falling on the VFS surface and mixing with herbicide runoff undoubtedly contributes to concentration changes (Kloppel et al. 1997; Schmitt et al. 1999). In addition, dilution effects associated with throughfall seepage may occur. Yet, there is considerable evidence for the sorption of moderately sorbed herbicides to the VFS grass, grass thatch, and soil surface (Asmussen et al. 1977; Lowrance et al. 1997; Misra et al. 1996; Vellidis et al. 2002). Consequently, unless specifically addressed in the reviewed manuscript as otherwise, the authors assume that concentration changes between VFS inflow and VFS outflow are attributed to a sorption mechanism.

Filter Strip Properties

General Effectiveness

In all but two manuscripts (Rankins et al. 2001; Seybold et al. 2001), the presence of a VFS reduced the transport of herbicides by at least 27% compared with control plots. In these experiments, control plots had either no filter strip (Hall et al. 1983; Patty et al. 1997; Rankins et al. 2001; Tingle et al. 1998) or consisted of a nonvegetated, untilled area of equal dimensions to the VFS treatment (Mersie et al. 1999b; Seybold et al. 2001). In a natural rainfall study, Hall et al. (1983) concluded that losses of atrazine were reduced by 91% in plots containing 1.8- by 6-m oat (*Avena sativa* L.) filter strips. Losses of atrazine, desethylatrazine, and deisopropylatrazine were reduced by at least 44% in ryegrass (*Lolium perenne* L.) filter strips ranging in size from 30 to 120 m^2 (Patty et al. 1997). Similar results were reported for the retention of metribuzin and metolachlor in

TABLE 1. Nomenclature and relevant properties of herbicides mentioned in the text or tables.

Herbicide family	Herbicide common name	Solubility	p*Ka*	K_{ow}[a]	K_{oc}	Sorption[b]
		mg L^{-1}				
Benzamide	Isoxaben	1[c]	None	434[c]	380[c]	M
Chloroacetamide	Alachlor	242[c]	None	794[c]	124[c]	M
	Metolachlor	450[c]	None	309[c]	75[c]	M
	Metolachlor oxanilic acid	8,500[d]	2.8[d]	NR	25[e]	M
	Metolachlor ethanesulfonic acid	NR[f]	NR	NR	26[e]	M
Dinitroaniline	Trifluralin	0.30[c]	None	118,000[c]	7,000[c]	S
Diphenylether	Bifenox	0.40[a]	None	31,700[c]	10,000[c]	S
None accepted	Diflufenican	0.05[c]	None	79,432[c]	2,000[c]	S
Phenoxy	Dichlorprop	710[c]	2.86[c]	NR	1,000[c]	M
	2,4-D	900[c]	2.8[c]	NR	20[c]	M
Phenylurea	Fluometuron	110[c]	None	242[c]	100[c]	M
	Isoproturon	65[c]	None	316[c]	155[c]	M
Pyridazinone	Norflurazon	28[c]	None	280[c]	700[c]	M
Triazines	Atrazine	33[c]	1.7[c]	481[c]	100[c]	M
	Cyanazine	165[c]	5.1[c]	127[c]	190[c]	M
	Diaminoatrazine	NR	NR	NR	NR	NR
	Desethylatrazine	330[g]	NR	NR	95[h]	M
	Deisopropylatrazine	> 330[g]	NR	NR	129[h]	M
	Hydroxyatrazine	6 pH 13[g]	NR	NR	248[i]	M
	Metribuzin	1,100[c]	None	40[c]	52[c]	M
Triazinylsulfonylurea	Metsulfuron	1 pH 5[c] 0.02 pH 7	3.3[c]	1 pH 5[c] 0.02 pH 7	35[c]	M

[a] Water solubility at 25 C unless otherwise stated.
[b] Sorption of herbicides to soil classified as moderate (M) or strong (S) on the basis of K_{oc} and water solubility values.
[c] Vencill (2002).
[d] D. Tierney, personal communication.
[e] Krutz et al. (2004b).
[f] NR = none reported.
[g] Hernandez et al. (1997).
[h] Seybold and Mersie (1996).
[i] Krutz et al. (2003a).

tall fescue (*Festuca arundinacea* Schreb.) filter strips ranging in size from 2 to 16 m^2 (Tingle et al. 1998; Webster and Shaw 1996). In a natural rainfall study periodically augmented with simulated rainfall, Rankins et al. (2001) reported that losses of fluometuron were reduced by at least 59% in 4- by 2-m filter strips established in big bluestem (*Andropogon gerardii* Vitman.), eastern gamagrass (*Tripsacum dactyloides* L.), switchgrass (*Panicum virgatum* L.), and tall fescue. In that same study, losses of norflurazon were reduced by at least 63% by big bluestem and eastern gamagrass filter strips (Rankins et al. 2001). In a simulated run-on experiment, 0.9- by 2-m switchgrass filter strips reduced losses of atrazine and metolachlor by 27% (Mersie et al. 1999b). Although these data indicate the potential for VFS to abate herbicide runoff, the majority of these experiments have been conducted at the mesoplot ($\leq$ 0.1 ha) and microplot scale (< 1 to 10 m^2). Moreover, no study has documented a decline in herbicide concentrations in receiving water bodies in response to the installation of filter strips. Thus, there is a need to quantify the reduction of herbicides in surface water bodies in response to the installation of VFS at the watershed scale (heterogeneous areas to many square kilometers).

Strip Width

The retention of sediment as a function of VFS width is nonlinear, with substantial retention occurring in the first few meters but little additional retention as width increases beyond approximately 5 m (Abu-Zreig 2001; Barfield et al. 1998; Dillaha et al. 1989; Magette et al. 1989; Patty et al. 1997; Schmitt et al. 1999; Tingle et al. 1998). In computational (Abu-Zreig 2001) and field studies (Daniels and Gilliam 1996; Schmitt et al. 1999), sediment trapping in VFS was correlated with sediment size, increasing in the order of clay < silt < sand. The implication is that herbicides transported with finer sediments, including the fine-silt and clay fraction, may reach the VFS outflow regardless of width (Hayes et al. 1984; Peterjohn and Correll 1984; Schmitt et al. 1999).

Disregarding studies with high infiltration variability (Kloppel et al. 1997) and relatively small maximum VFS widths (Tingle et al. 1998), data indicate a positive correlation between VFS width and retention of moderately sorbed herbicides and herbicide metabolites including atrazine (Barfield et al. 1998; Patty et al. 1997; Schmitt et al. 1999), desethylatrazine (Patty et al. 1997), deisopropylatrazine (Patty et al. 1997), and alachlor (Schmitt et al. 1999). In studies where VFS width was doubled or tripled, herbicide retention increased by at least 38% (Patty et al. 1997; Schmitt et al. 1999). The proposed mechanism for enhanced retention of herbicides at wider VFS widths is a greater opportunity for infiltration (Barfield et al. 1998; Schmitt et al. 1999) and sorption to VFS sorbents (Barfield et al. 1998).

Table 2. Predominant species established in vegetative filter strips.

Scientific name	Common name	Reference
Grasses		
Andropogon gerardii Vitman.	Big bluestem	Rankins et al. (2001)
Avena sativa L.	Oats	Hall et al. (1983)
Bromus inermis Leyss.	Bromegrass	Arora et al. (1996, 2003), Boyd et al. (2003), Schmitt et al. (1999)
Buchloe dactyloides Nutt. Englem	Buffalograss	Krutz et al. (2003a, 2004b), Wolfe et al. (2000)
Cynodon dactylon L.	Bermudagrass	Asmussen et al. (1977), Lowrance et al. (1997), Rhode et al. (1980), Vellidis et al. (2002)
Festuca arundinacea Schreb.	Tall fescue	Arora et al. (1996, 2003), Barfield et al. (1998), Boyd et al. (2003), Rankins et al. (2001), Schmitt et al. (1999), Tingle et al. (1998), Webster and Shaw (1996)
Lolium perenne L.	Ryegrass	Benoit et al. (1999), Lowrance et al. (1997), Patty et al. (1997)
Panicum virgatum L.	Switchgrass	Mersie and Seybold (1997, 1999b), Rankins et al. (2001), Schmitt et al. (1999), Seybold et al. (2001)
Paspalum notatum Poir.	Bahiagrass	Asmussen et al. (1977), Lowrance et al. (1997), Rhode et al. (1980), Vellidis et al. (2002)
Poa pratensis L.	Kentucky bluegrass	Arora et al. (1996, 2003), Barfield et al. (1998), Boyd et al. (2003)
Tripsacum dactyloides L.	Eastern gamagrass	Rankins et al. (2001)
Trees and shrubs		
Acer saccharinum L.	Silver maple	Schmitt et al. (1999)
Fraxinus pennsylvanica L.	Green ash	Vellidis et al. (2002)
Liriodendron tulipifera L.	Yellow poplar	Vellidis et al. (2002)
Lonicera maackii (Rupr.) Herder	Bush honeysuckle	Schmitt et al. (1999)
Nyssa sylvatica var. *biflora* Marsh.	Swamp black gum	Lowrance et al. (1997), Vellidis et al. (2002)
Pinus palustris Mill.	Long leaf pine	Lowrance et al. (1997), Vellidis et al. (2002)
Pinus elliottii Engelm.	Slash pine	Lowrance et al. (1997), Vellidis et al. (2002)
Pinus rigida L.	Yellow pine	Lowrance et al. (1997)
Populus deltoides Bartr.	Eastern cottonwood	Schmitt et al. (1999)
Ribes aureum Pursh.	Golden currant	Schmitt et al. (1999)

Area Ratio

The area ratio is defined as the ratio between the surface area contributing to runoff and the surface area of the VFS. Runoff volume, runoff rate, and herbicide loading are positively correlated with the area contributing to runoff. The implication is that the ability of the VFS to retard runoff, reduce sediment transport, increase time for infiltration, and prolong contact time between herbicides and sorbents decreases as the area ratio increases.

To date, the effect of area ratio on VFS efficacy has been evaluated by maintaining the width of the VFS while manipulating runoff flow rate. In a simulated run-on study, Misra et al. (1996) compared the retention of atrazine, metolachlor, and cyanazine in 1.5- by 12.2-m bromegrass (*Bromus inermis* Leyss.) filter strips at an inflow rate of 57 L min^{-1} (area ratio of 15:1) and 114 L min^{-1} (area ratio of 30:1). Retention of all compounds was $\leq$ 41% and was independent of flow rate. In a companion study, herbicide runoff from the source area was generated by natural rainfall and then directed onto 1.5- by 20.1-m bromegrass filter strips with a sheet-flow applicator (Arora et al. 1996). The retention of atrazine, metolachlor, and cyanazine was not different between the 15:1 and 30:1 area ratios. Similar results were reported for the retention of atrazine, metolachlor, and the strongly sorbed insecticide chlorpyrifos by bromegrass filter strips with area ratios of 15:1 and 30:1 (Arora et al. 2003). Boyd et al. (2003) evaluated the retention of atrazine, acetochlor, and chlorpyrifos by bromegrass filter strips with area ratios of 15:1 and 45:1. Retention of moderately sorbed herbicides was not different between area ratios, but retention of chlorpyrifos was greater at an area ratio of 15:1 compared with 45:1. Enhanced retention of chlorpyrifos at a narrower area ratio was attributed to lower flow volumes and rates, which facilitated sedimentation. The retention of copper (Wu et al. 2003) and the strongly sorbed insecticide endosulfan (Mersie et al. 2003) was evaluated as a function of vegetation established in the strip and flow rate. For both fescue and switchgrass filter strips, the retention of copper and endosulfan was greater at a flow rate of 2.7 L min^{-1} compared with 6 L min^{-1}. Enhanced retention of copper and endosulfan at slower flow rate was attributed to a greater opportunity for infiltration and sorption.

Currently, our understanding of VFS efficacy as a function of flow rate is limited to extreme conditions, either inundation of the VFS where efficacy is severely compromised or total infiltration resulting in 100% efficacy. Between these two extremes, where the majority of experiments are conducted, our understanding of the retention process is obscured by the inability to adequately control for experimental error associated with infiltration and our ig-

TABLE 3. Factors reported to affect the retention of herbicides in vegetative filter strips.

Factor	Comment	Reference
Presence of a vegetated filter strip	The transport of herbicides and herbicide metabolites was reduced by at least 43% in plots containing vegetative filter strips and was attributed to infiltration, sedimentation, or sorption in the strip (or all)	Hall et al. (1983), Patty et al. (1997), Rankins et al. (2001), Tingle et al. (1998), Webster and Shaw (1996)
Width of vegetated filter strip	Generally, data indicate a positive correlation between vegetative filter strip width and retention of herbicides. The relationship is attributed to a greater opportunity for infiltration or sorption (or both) at wider widths. Exceptions include experiments where infiltration is highly variable among plots, the maximum width evaluated does not exceed 4 m, and strongly sorbed herbicides are evaluated	Barfield et al. (1998), Kloppel et al. (1997), Mickelson et al. (2003), Patty et al. (1997), Schmitt et al. (1999), Tingle et al. (1998)
Vegetation established in strip	Two studies evaluated herbicide retention as a function of plant species established in the filter strip. Herbicide trapping efficiency was not different among four perennial grass species or between 2-yr-old grass and a 2-yr-old grass–shrub–tree mixture	Rankins et al. (2001), Schmitt et al. (1999)
Source area to vegetated filter strip area ratio	Source area to vegetative filter strip area ratios reported in the literature range from 5:1 to 45:1. Seventy-five percent of the manuscripts report no difference in the retention of moderately sorbed herbicides as a function of area ratio. Exceptions included greater retention of atrazine at an area ratio of 5:1 compared with 10:1 and greater retention of strongly sorbed compounds an at area ratio of 15:1 compared with 45:1. Generally, the inability to detect differences between treatments was attributed to variable infiltration rates among plots	Arora et al. (1996, 2003), Boyd et al. (2003), Misra et al. (1996)
Inflow herbicide concentration	The retention of atrazine, metolachlor, and cyanazine was greater at an inflow concentration of 1.0 mg L^{-1} compared with 0.1 mg L^{-1}. Greater retention of these herbicides at higher inflow concentrations was attributed to sorption to in-place soil or to living or dead plant tissue (or both)	Misra et al. (1996)
Herbicide properties	Because of sedimentation within the vegetative filter strip, strongly sorbed compounds are retained to a greater extent than moderately sorbed compounds. Among the moderately sorbed herbicides, compounds that are nonionic or have low water solubilities are retained to a greater extent than species that are anionic or have high water solubilities (or both). This has been attributed to hydrophobic interactions with in-place soil or to living or dead plant materials or both	Arora et al. (1996, 2003), Boyd et al. (2003), Kloppel et al. (1997), Krutz et al. (2003a, 2004b), Misra et al. (1996), Patty et al. (1997), Rankins et al. (2001), Schmitt et al. (1999), Seybold et al. (2001), Tingle et al. (1998), Webster and Shaw (1996)
Antecedent moisture	Because of reduced infiltration at high soil moisture contents, herbicide retention is generally negatively correlated with the vegetated filter strip's antecedent moisture content	Asmussen et al. (1977), Rhode et al. (1980)

norance of herbicide sorption to VFS sorbents during nonequilibrium conditions. Experimental error associated with infiltration may be reduced if field plots are selected on a prior knowledge of infiltration rate and variability. Sorption of herbicides to VFS grass, grass thatch, or the soil surface (or all) under nonequilibrium conditions may be elucidated using a nonequilibrium thin-disc apparatus, as described by Smith et al. (2003), in place of the traditional batch equilibrium technique.

Vegetation Type

The effect of vegetation type on the retention of herbicides in VFS has been evaluated in two studies. In a natural rainfall study periodically augmented with simulated rainfall, Rankins et al. (2001) reported that the retention of sediment, fluometuron, and norflurazon was not different among 4- by 2-m filter strips established in big bluestem, eastern gamagrass, switchgrass, or tall fescue. From data generated from a simulated run-on experiment, Schmitt et al. (1999) reported that the retention of sediment, atrazine, and alachlor was not different among 3- by 7.5-m and 3- by 15-m filter strips established in either mixed grasses (switchgrass and tall fescue) or one-half grasses (switchgrass and tall fescue) and one-half trees and shrubs [eastern cottonwood, *Populus deltoids* Bartr., silver maple, *Acer saccharinum* L., bush honeysuckle, *Lonicera maackii* (Rupr.) Herder, and golden currant, *Ribes aureum* Pursh.]. Despite the limited amount of work conducted in this area, there is considerable indirect evidence indicating that the type of

Table 4. Vegetation evaluated for the ability to enhance the degradation of herbicides in soil.

Scientific name	Common name	Herbicide	Reference
Vegetation did not increase degradation of herbicide			
Abutilon theophrasti Medicus	Velvetleaf	Atrazine, metolachlor	Anderson and Coats (1995)
Amaranthus sp.	Pigweed	Atrazine, metolachlor	Anderson and Coats (1995)
Carduus nutans L.	Musk thistle	Metolachlor	Anderson and Coats (1995)
Chenopodium album L.	Common lambsquarters	Metolachlor	Anderson and Coats (1995)
Conyza canadensis L. Cronqu.	Horseweed	Atrazine, metolachlor	Anderson and Coats (1995)
Echinochloa crus-galli L. Beauv.	Barnyardgrass	Atrazine, metolachlor	Anderson and Coats (1995)
Glycine max L. Merr.	Soybean	Atrazine, metolachlor, trifluralin	Anderson et al. (1994b)
Hibiscus trionum L.	Venice mallow	Atrazine, metolachlor	Anderson and Coats (1995)
Hordeum jubatum L.	Foxtail barley	Metolachlor	Anderson and Coats (1995)
Lepidium latifolium L.	Pepperweed	Atrazine, metolachlor	Anderson and Coats (1995)
Nepeta cataria L.	Catnip	Metolachlor	Anderson and Coats (1995)
Panicum capillare L.	Witchgrass	Metolachlor	Anderson and Coats (1995)
Panicum virgatum L.	Switchgrass	Atrazine	Mersie et al. (1999b)
Polygonum pennsylvanicum	Smartweed	Atrazine, metolachlor	Anderson and Coats (1995)
Setaria glauca L. Beauv.	Yellow Foxtail	Atrazine, metolachlor	Anderson and Coats (1995)
Zea mays L.	Corn	Metolachlor	Anderson and Coats (1995)
Vegetation enhanced the degradation of herbicide			
Chenopodium album L.	Common lambsquarters	Atrazine	Anderson and Coats (1995)
Carduus nutans L.	Musk thistle	Atrazine, metsulfuron	Anderson and Coats (1995), Ghani and Wardle et al. (2001)
Hordeum jubatum L.	Foxtail barley	Atrazine	Anderson and Coats (1995)
Kochia scoparia L. Schrad.	Kochia	Atrazine, trifluralin	Anders et al. (1994a, 2000), Perkovich et al. (1996)
Lolium perenne L.	Ryegrass	Isoproturon, fluometuron	Benoit et al. (1999), Wagner and Zablotowicz (1997a, 1997b)
Nepeta cataria L.	Catnip	Atrazine	Anderson and Coats (1995)
Oryza sativa L.	Rice	Fluometuron	Wagner and Zablotowicz (1997a)
Panicum capillare L.	Witchgrass	Atrazine	Anderson and Coats (1995)
Panicum virgatum L.	Switchgrass	Metolachlor	Mersie et al. (1999b), Seybold et al. (2001)
Populus deltoides nigra DN34	Poplar	Atrazine	Burken and Schnoor (1996)
Vicia villosa Roth.	Hairy vetch	Fluometuron	Wagner and Zablotowicz (1997a)
Zea mays L.	Corn	Alachlor, metolachlor	Hoagland et al. (1997)
Conflicting reports among experiments			
Kochia scoparia L. Schrad	Kochia	Metolachlor	Anderson and Coats (1995), Anderson et al. (1994a, Arthur et al. 2000)
Panicum virgatum L.	Switchgrass	Atrazine	Mersie et al. (1999a, 1999b), Seybold et al. (2001)
Zea mays L.	Corn	Atrazine	Anderson and Coats (1995), Costa et al. (2000), Marchand et al. (2002)

vegetation established in the VFS may affect herbicide retention efficacy.

Herbicides entering the VFS are retained by sedimentation, infiltration, and sorption to leaves, stems, and thatch. These retention mechanisms are interconnected. Species that physically reduce the flow of surface runoff decrease sediment transport capacity while increasing the opportunity for infiltration and sorption. Similarly, species that enhance soil infiltration rates decrease surface runoff velocity, facilitate sedimentation, encourage the leaching of moderately sorbed herbicides, and promote sorption by increasing the contact time between dissolved phase herbicides and VFS sorbents (Lee et al. 2000; Mukhtar et al. 1985; Schultz et al. 1995).

Differences in the ability of vegetation to retard surface runoff, promote infiltration, and sorb herbicides have been noted in the literature. Generally, tall, stiff grasses with high stem density form deeper ponds, reduce more flow, and are potentially more efficacious under high flow conditions compared with relatively short or limber grass species (Meyer et al. 1995). Bharati et al. (2002) reported that 60-min cumulative infiltration rates for a riparian buffer decreased in the order of silver maple > mixed stand of smooth brome–timothy (*Phleum pratense* L.)–Kentucky bluegrass

TABLE 5. Factors governing the environmental fate of herbicides in vegetative filter strips.

Factor	Comment	Reference
Leaching	There is potential for greater preferential flow of herbicide runoff in vegetative filter strip soil compared with adjacent cultivated soil. However, the leaching of nonionic herbicides in vegetative filter strip soil may be lower than in adjacent cultivated soil because of enhanced sorption and degradation in the former. The leaching of ionic herbicides has not been studied	Benoit et al. (2000), Delphin and Chapot (2001), Mersie et al. (1999a), Reungsan et al. (2002)
Adsorption	Higher organic carbon content in vegetative filter strip soil compared with adjacent cultivated soil enhances the sorption of nonionic herbicides. In addition, the sorption of nonionic herbicides to vegetative filter strip constituents including leaves, stems, and thatch is greater than that for cultivated soil. However, the sorption of anionic species is governed primarily by clay mineral surfaces rather than organic carbon content; thus, the sorption of anionic species may not be enhanced in vegetative filter strip soils	Benoit et al. (1999), Blanche et al. (2003), Dozier et al. (2002), Krutz et al. (2003b, 2004a), Mersie et al. (1999a), Rankins et al. (2002), Reungsang et al. (2001), Staddon et al. (2001)
Desorption	Generally, the desorption of nonionic herbicides from vegetative filter strip soil is lower than that of adjacent cultivated soil and has been attributed to higher levels of organic carbon in vegetative filter strip soil. However, the desorption of anionic species is not different between vegetative filter strip and cultivated soil	Benoit et al. (2001), Krutz et al. (2003b, 2004a), Rankins et al. (2002), Staddon et al. (2001)
Microbial parameters	Estimates for microbial activity (respiration and soil enzyme activity) are generally higher in vegetative filter strip soil compared with adjacent cultivated soil	Benoit et al. (1999, 2000), Staddon et al. (2001), Reungsang et al. (2001)
Degradation	Several herbicides (isoproturon, atrazine, metolachlor, and fluometuron) exhibited accelerated degradation in vegetative filter strip soil compared with adjacent cultivated soil. Two exceptions: experiments whereby vegetation in the filter strip had been established for ≤ 1 growing season and experiments in which the cultivated soil had developed an active atrazine-degrader population	Benoit et al. (1999, 2000), Mersie et al. (1999a, 1999b), Reungsang et al. (2001), Seybold et al. (2001), Shankle et al. (2001), Staddon et al. (2001)
Bound residue formation	Accumulation of organic matter in vegetative filter strip soil compared with adjacent cultivated soil enhances the formation of bound residues	Benoit et al. (1999, 2000), Reungsang et al. (1999), Staddon et al. (2001)

(*Poa pratensis* L.) > switchgrass. Under low flow conditions, Mersie et al. (2003) and Wu et al. (2003) observed greater infiltration rates under filter strips established in fescue compared with switchgrass. Reddy et al. (1995) reported higher Freundlich sorption coefficients for hairy vetch (*Vicia villosa* Roth) residues (6.33) compared with rye grass residues (3.95). Greater sorption of atrazine (Dozier et al. 2002), metolachlor (Dozier et al. 2002), and fluometuron (Blanche et al. 2003) is reported for bermudagrass (*Cynodon dactylon* L.) thatch (Dozier et al. 2002) switchgrass thatch (Blanche et al. 2003), and switchgrass stems (Blanche et al. 2003) compared with adjacent cultivated soils (CS) (Blanche et al. 2003; Dozier et al. 2002) and VFS soil (Blanche et al. 2003). Combined, these data indicate the need to evaluate plant species for establishment in filter strips on the basis of their ability to physically retard surface runoff, enhance soil quality parameters (i.e., infiltration rate, OM accumulation, aggregate stability, bulk density, etc.), and promote sorption of herbicides to grass leaves, stems, and thatch.

Time After Establishment

When VFS are established, tillage is discontinued and vegetation is maintained contentiously. Above- and belowground plant residues accumulate in the VFS and increase soil OM content (Benoit et al. 1999; Blanche et al. 2003; Krutz et al. 2003b, 2004a; Rankins et al. 2002; Staddon et al. 2001). Decomposing plant residues enhance the size and stability of soil aggregates (Angers et al. 1993; Beare et al. 1994; Weill et al. 1988). Because of the lack of tillage and the presence of continuous vegetation, interconnected macropores are formed via microfauna and decomposing root systems (Drees et al. 1994; Edwards et al. 1988; Haines and Uren 1990). Greater macropore formation and aggregate stability in the VFS enhance soil porosity, infiltration capacity, and herbicide retention. Thus, one may expect older, more established VFS to be more efficacious than younger, newly established VFS. However, the ability of the VFS to function properly over time largely depends on the erodibility of the source area and the willingness and ability of the landowner or operator to maintain the VFS (Hayes and Dillaha 1992).

The deposition of sediment at the cultivated field–VFS interface and within the VFS proper decreases VFS efficacy. Dillaha et al. (1989) noted that sediment deposited at the cultivated field–VFS interface may act as a dike that diverts subsequent field runoff to low points along the VFS where it enters the VFS as channel flow rather than sheet flow. In addition, as the VFS is progressively inundated with sediment, its effectiveness in removing sediment, P, and N decreases (Dillaha et al. 1988; Jin et al. 2002; Magette et al. 1989). To minimize reduced efficacy of the VFS over time, the VFS must be inspected and repaired after major storm events (Hayes and Dillaha 1992). When sediment losses from fields up-slope of the VFS are expected to exceed 22.5 Mg ha^{-1}, the implementation of in-field BMP may be required (Hayes and Dillaha 1992).

There are several in-field BMP that reduce off-site transport of sediment that could be used in conjunction with

VFS in an attempt to maintain or improve their efficacy (or both) over time. Conservation tillage is a management practice that excludes at least one major cultivation practice or minimizes the intensity of tillage operations (Locke and Bryson 1997). Compared with conventional tillage, conservation tillage practices significantly reduce soil erosion (Gaynor and Findlay 1995; Intarapapong et al. 2002; Myers and Wagger 1996; Seta et al. 1993). In addition, conservation tillage practices could be used in concert with contour buffers, grass hedges, and grassed waterways. Contour buffers are wide strips of grass installed along topographic contours within the field proper. Renard et al. (1997) indicated that properly installed contour buffer strips in contour-tilled fields reduce off-site sediment transport by approximately half. Similarly, grass hedges (narrow [1 to 2 m wide], stiff, erect, grass established near to or on the contour of fields) are reported to retard and disperse surface runoff, cause deposition of eroded sediment, and reduce ephemeral gully development (Dabney et al. 1995, 1999; Gilley et al. 2000). Grassed waterways (strips of grasses and nonwoody perennial vegetation established in areas where runoff water concentrates within the field proper) prevent gully erosion and effectively reduce sediment transport (Fiener and Auerswald 2003).

Antecedent Moisture Content

Asmussen et al. (1977) evaluated 2,4-D retention by 4.6- by 24.4-m bermudagrass–bahiagrass (*Paspalum notatum* Poir.) filter strips under wet and dry antecedent moisture levels. Regardless of moisture level, inflow sediment loads were reduced by 94%. The mass of 2,4-D retained by infiltration was greater under dry VFS conditions (25%) compared with wet VFS conditions (2%). The amount of 2,4-D retained by a sorption mechanism was 46% under dry conditions and 67% under wet conditions. Greater retention of 2,4-D by a sorption mechanism under wet conditions was likely due to the higher inflow herbicide concentration under wet conditions (940 $\mu g\ L^{-1}$) compared with the concentration under dry conditions (164 $\mu g\ L^{-1}$). In a companion study, similar results were reported for the retention of trifluralin (Rhode et al. 1980).

Nominal Inflow Concentration

There appears to be a direct correlation between nominal inflow concentration and the retention of herbicides transported primarily in the dissolved phase of surface runoff. The average retention of atrazine, metolachlor, and cyanazine by 1.5- by 12.2-m bromegrass filter strips at nominal inflow concentrations of 0.1 and 1.0 mg L^{-1} was 29 and 46%, respectively (Misra et al. 1996). Similar results were reported for the retention of terbuthylazine, isoproturon, and dichlorprop-p at inflow concentrations of 50 and 200 $\mu g\ L^{-1}$ (Kloppel et al. 1997). These data indicate at higher inflow concentrations that the probability of herbicide and sorbent contact increases, resulting in greater retention by a sorption mechanism. Results from these studies indicate that it may be invalid to compare the retention of different herbicides by VFS when their nominal inflow concentrations cannot be controlled (i.e., natural rainfall, simulated rainfall, and simulated run-on experiments whereby herbicide is applied to the source area).

Herbicide Properties

Numerous studies have reported data for the retention of more than one herbicide or sediment (or both) by a given VFS treatment (Arora et al. 1996, 2003; Boyd et al. 2003; Kloppel et al. 1997; Krutz et al. 2003a, 2004b; Lowrance et al. 1997; Mersie et al. 1999b; Misra et al. 1996; Patty et al. 1997; Rankins et al. 2001; Schmitt et al. 1999; Seybold et al. 2001; Tingle et al. 1998; Vellidis et al. 2002; Webster and Shaw 1996). Of these studies, 25% were designed in a manner whereby the nominal herbicide inflow concentration was controlled (Arora et al. 1996; Kloppel et al. 1997; Krutz et al. 2003a, 2004b). Because herbicide inflow concentration influences relative trapping efficiency, it is difficult, if not inappropriate, to compare relative trapping efficiency among compounds for a study where nominal inflow concentration is not controlled. Yet, several broad generalizations can be drawn from these data.

There are obvious differences in the retention of strongly sorbed and moderately sorbed herbicides by VFS. Data clearly indicate that the retention of sediment by VFS is greater than that of water. Thus, the retention of strongly sorbed herbicides transported primarily by sediment is to a greater extent than the moderately sorbed herbicides transported primarily in the dissolved phase of surface runoff (Arora et al. 2003; Boyd et al. 2003; Mickelson et al. 2003; Patty et al. 1997; Rankins et al. 2001; Schmitt et al. 1999; Tingle et al. 1998; Webster et al. 1996). Generally, there does not appear to be differences in the retention of moderately sorbed herbicides including metolachlor (Arora et al. 1996; Mersie et al. 1999b; Misra et al. 1996; Seybold et al. 2001; Tingle et al. 1998; Webster et al. 1996), atrazine (Arora et al. 1996; Lowrance et al. 1997; Mersie et al. 1999b; Patty et al. 1997; Schmitt et al. 1999; Seybold et al. 2001; Vellidis et al. 2002), cyanazine (Arora et al. 1996; Misra et al. 1996), alachlor (Lowrance et al. 1997; Vellidis et al. 2002), metribuzin (Tingle et al. 1998; Webster et al. 1996), fluometuron (Rankins et al. 2001), and norflurazon (Rankins et al. 2001). However, the ability to detect differences in the retention of moderately sorbed herbicides is difficult to elucidate because most experiments do not control for nominal inflow concentration.

When retention differences among moderately sorbed herbicides are narrowed to experiments where nominal inflow concentration is controlled, data indicate that VFS efficacy may differ among compounds. Kloppel et al. (1997) evaluated the retention of terbuthylazine, isoproturon, and dichlorprop-p in VFS at nominal inflow concentrations of 50 and 200 $\mu g\ L^{-1}$. Generally, herbicide concentrations at the VFS outflow decreased as a function of water solubility: dichlorprop-p (710 mg L^{-1}) > isoproturon (65 mg L^{-1}) > terbuthylazine (8.5 mg L^{-1}). Krutz et al. (2003a) evaluated the retention of atrazine, diaminoatrazine, deisopropylatrazine, desethylatrazine, and hydroxyatrazine by 1- by 3-m buffalograss (*Buchloe dactyloides* Nutt. Englem) filter strips at a nominal inflow concentration of 100 $\mu g\ L^{-1}$. The relative trapping efficiency of atrazine was greater than that of its metabolites. Generally, retention decreased as water solubility increased or hydrophobicity decreased (or both). In a companion study, Krutz et al. (2004b) compared the retention of metolachlor, metolachlor ethanesulfonic acid, and metolachlor oxanilic acid by 1- by 3-m buffalograss filter strips at a nominal inflow concentration of 120 $\mu g\ L^{-1}$.

Retention of the nonionic parent compound was greater than that of the two ionic metabolites. Again, retention decreased as water solubility increased or hydrophobicity decreased (or both). These data indicate that differences in the retention of moderately sorbed herbicides by VFS can occur when the compounds evaluated differ substantially in water solubility, hydrophobicity, or ionic nature (or all).

Environmental Fate

Adsorption–Desorption

VFS have properties similar to a natural prairie ecosystem and accumulate both surface- and belowground OM. Generally, higher organic carbon contents in VFS soil compared with adjacent CS have been shown to significantly enhance the sorption of nonionic and weakly basic herbicides and herbicide metabolites. Greater sorption of metolachlor (Krutz et al. 2004a; Staddon et al. 2001), fluometuron (Blanche et al. 2003; Rankins et al. 2002; Shankle et al. 2004), isoproturon (Benoit et al. 1999), atrazine (Krutz et al. 2003a; Reungsang et al. 2001), and hydroxyatrazine (Krutz et al. 2003a) has been reported for VFS soil compared with adjacent CS. In these studies, desorption of atrazine (Krutz et al. 2003a), isoproturon (Benoit et al. 1999), fluometuron (Rankins et al. 2002), and metolachlor (Krutz et al. 2004a; Staddon et al. 2001) was greater for CS compared with VFS. Because sorption of herbicides to soil is inversely correlated with mobility, these data indicate reduced mobility of these compounds in VFS soil compared with adjacent CS. Exceptions to these trends include two monodealkylated metabolites of atrazine, desethylatrazine and deisopropylatrazine, and two ionic metabolites of metolachlor, metolachlor ethanesulfonic acid and metolachlor oxanilic acid. Sorption and desorption coefficients for these metabolites were not different between VFS and adjacent CS (Krutz et al. 2003a, 2004a). The implication is that elevated levels of organic carbon in VFS soil will not significantly reduce the mobility of herbicides or herbicide metabolites (or both) that are ionic or considerably polar (or both) because factors other than OM control their sorption (i.e., clay mineral surfaces, iron oxides, etc.).

Microbiological Parameters and Herbicide Degradation

The presence of perennial vegetation, rhizodeposition of labile organic substrates, and accumulation of an organic residue thatch layer enhances soil microflora and their metabolic activity compared with CS. In most studies, microbial numbers, microbial activity, and soil enzymatic activity are generally higher in VFS soil compared with adjacent CS. Staddon et al. (2001) observed higher microbial numbers (total bacteria, total fungi, gram-negative bacteria, and fluorescent pseudomonads), total microbial heterotrophic activity (estimated by fluorescein diacetate), microbial metabolic activity (estimated by triphenyl-tetrazolium chloride dehydrogenase activity), alkaline phosphatase activity, and aryl acylamidase activity for soil collected from a 6-yr-old hairy vetch filter strip compared with an adjacent CS. Benoit et al. (1999) observed higher microbial respiratory activity (C-CO_2) in soil collected from a perennial ryegrass filter strip compared with an adjacent CS. The enriched density of several classes of soil microflora and indexes of microbial activity in VFS compared with adjacent CS indicates potential for enhanced degradation of herbicides. Specifically, higher aryl acylamidase activity indicates a greater potential for degradation of herbicides such as metolachlor, propanil, and linuron (Staddon et al. 2001; Zablotowicz et al. 1998). Higher fluorescein diacetate activity is associated with a greater active microbial biomass (Schnurer and Roswall 1982) and is indicative of a greater potential for herbicide ester bond cleavage (Zablotowicz et al. 2000).

In most instances, researchers have reported enhanced degradation of herbicides in VFS compared with adjacent CS. Staddon et al. (2001) observed greater degradation of metolachlor from soil collected from a 6-yr-old hairy vetch filter strip compared with an adjacent CS. Reported half life values ($T_{1/2}$) for metolachlor were 18 d for the VFS soil and 38 d for the CS, but cumulative $^{14}CO_2$ mineralization from ^{14}C-ring-labeled metolachlor was $\leq 4\%$ for both soils. Shankle et al. (2001) reported that the $T_{1/2}$ value for fluometuron dissipation was 11 d in soil collected from a 5-yr-old tall fescue filter strip compared with 111 d for soil collected from an adjacent CS. Mersie et al. (1999b) observed greater dissipation of metolachlor and atrazine in filter strips established in switchgrass compared with nonvegetated soil. In a companion study, Seybold et al. (2001) reported enhanced degradation of metolachlor in filter strips established in fescue compared with nonvegetated soil, but the degradation of atrazine was not different between soils. Benoit et al. (1999) observed enhanced degradation of isoproturon from soil collected from a perennial ryegrass filter strip compared with an adjacent CS. Reported $T_{1/2}$ values were 72 d for 0- to 15-cm CS, 8 d for 0- to 2-cm VFS soil, 20 d for 2- to 6-cm VFS soil, and 26 d for 6- to 13-cm VFS soil. Cumulative mineralization of isoproturon after 35 d of incubation decreased in the order of 20% for 0- to 2-cm VFS soil, 8% for 2- to 6-cm VFS soil, 5% for 6- to 13-cm VFS soil, and less than 1% for CS. In a companion study, Benoit et al. (2000) duplicated the mineralization experiment but with intact soil columns rather than disturbed soil samples. Although the temperature (18 C), moisture content (90% of water holding capacity), and soils were identical between studies, the mineralization of isoproturon from intact soil columns was $\leq 1\%$ for both the VFS and CS. However, degradation of isoproturon was greater in VFS soil compared with CS. These data indicate that the potential for mineralization of herbicides may be overestimated when using disturbed soil samples.

In contrast to the studies described above, Reungsang et al. (2001) reported enhanced dissipation of atrazine in CS compared with soil collected from a 3-, 5-, and 9-yr-old switchgrass filter strip. Reported $T_{1/2}$ values for the 0- to 15-cm depth decreased in the order of 19 d for CS, 28 d for 5-yr-old VFS soil, 39 d for 9-yr-old VFS soil, and 52 d for 3-yr-old VFS soil. A similar trend was observed for the 15- to 30-cm depth. After 135 d of incubation, cumulative $^{14}CO_2$ evolution from uniformly ring-labeled ^{14}C-atrazine for the 0- to 15-cm depth decreased in the order of 60% for the CS, 12% for the 5-yr-old VFS soil, 2% for the 9-yr-old VFS soil, and 1% for the 3-yr-old VFS soil. A similar trend was observed for the 15- to 30-cm depth. They suggested that enhanced degradation of atrazine was because of the frequent application of atrazine to the CS, which facilitated and maintained the development of an active atrazine-degrading microbial population. This indicates that management practices applied to the source area will influence the relative ability of the VFS to serve as a herbicide sink. Mersie et al. (1999a) evaluated the effect of switchgrass roots on the mineralization of atrazine in Cullen (clayey, mixed thermic Typic Hapludults) and Emporia (fine-loamy, siliceous, thermic Typic Hapludults) soils. The mineralization of atrazine was $\leq 6\%$ for soil established with switchgrass for 9 mo and nonvegetated soil. These data indicate that VFS may need to be established for more than one growing season before enhanced degradation of herbicides can occur.

Although not yet evaluated in a VFS study, there is considerable evidence that enhanced degradation of herbicides in VFS soil may depend on the type of vegetation established in the strip. Several plant species have been evaluated for their ability to enhance the degradation of herbicide through a rhizosphere effect (Table 4). In a large scale screening study, Anderson and Coats (1995) evaluated the degradation of atrazine and metolachlor in rhizosphere soil collected from 15 plant species. Enhanced mineralization of atrazine was reported for rhizosphere soil collected from kochia (*Kochia scoparia* L. Schrad.), common lambsquarters (*Chenopodium album* L.), foxtail barley (*Hordeum jubatum* L.), witchgrass (*Panicum capillare* L.), catnip (*Nepeta cataria* L.), and musk thistle (*Carduus nutans* L.). Conversely, the mineralization of metolachlor was not different between rhizosphere and nonvegetated soil. In studies where identical plant species and herbicide combinations have been evaluated, conflicting reports are common (Table 4). Combined, these studies indicate the need to screen for the ability of species established in VFS to promote the degradation of herbicides through a rhizosphere effect. The implication is that species that promote the degradation of herbicides in the VFS will ultimately reduce the potential for their subsequent transport to surface and groundwater.

Certain herbicides are also subject to degradation in surface plant residues and thatch. Fluometuron is subject to rapid degradation via *N*-demethylation as rapidly in ryegrass cover crop residues as in soil provided sufficient moisture content; however, 2,4-D was relatively stable in rye or hairy vetch cover crop residues, whereas it was rapidly mineralized in soil (Zablotowicz et al. 1998). However, a winter cereal rye (*Secale cereale* L.) cover crop increased the potential for 2,4-D degradation in surface and subsurface of a Willamette silt loam soil (Bottomley et al. 1999). The effect of a winter cereal rye cover crop and time of soil sampling on the potential for 2,4-D degradation was assessed in surface and subsurface of a willamette silt loam (Bottomley et al. 1999). Populations of 2,4-D mineralizing bacteria were higher in the surface (0 to 20 cm) soil under cereal rye compared with winter fallow soil.

Plant Uptake

The uptake of herbicides by species established in filter strips has not been reported in the literature. Yet, the phytoremediation literature indicate that plant uptake may play a major role in the fate of herbicides retained in VFS. The uptake of atrazine (Burken and Schnoor 1996), metsulfuron (Ghani and Wardle 2001), trifluralin (Li et al. 2002), lindane (Li et al. 2002), and simazine (Wilson et al. 2000) by plant species has been reported. The species common to VFS and phytoremediation studies include poplar (*Populus deltoids nigra* DN34)) trees (Burken and Schnoor 1996) and ryegrass (Li et al. 2002). Burken and Schnoor (1996) reported that the majority of atrazine not tightly sorbed to the soil organic fraction was taken up by poplar trees. Similarly, significant uptake of trifluralin and lindane was reported for ryegrass (Li et al. 2002). These data indicate the need for future VFS studies to address the effect of plant uptake on the ultimate fate of herbicides in the filter strip.

Leaching

The fact that the retention of herbicides, particularly moderately sorbed compounds, by VFS is intimately linked with the infiltration process is a concern in that there is potential for contamination of shallow ground water. The detection of atrazine (Delphin and Chapot 2001; Lowrance et al. 1997; Vellidis et al. 2002), desethylatrazine (Delphin and Chapot 2001), and alachlor (Boyd et al. 2003; Lowrance et al. 1997; Paterson and Schnoor 1992; Vellidis et al. 2002) has been reported for shallow ground water beneath VFS. However, these studies did not address the relative transport of herbicides between VFS and CS. Benoit et al. (2000) evaluated the transport of isoproturon in intact soil columns collected from a CS and an adjacent ryegrass filter strip. The leaching of ^{14}C-labeled isoproturon was greater in the 7.6-cm-wide by 13-cm-long soil columns containing CS (47%) compared with VFS soil (31%). In a similar study (Reungsang et al. 2001), less atrazine was found in leachate from intact soil columns (20 cm in diameter and approximately 26 cm long) collected from 3- and 5-yr-old switchgrass filter strips (5%) compared with adjacent CS (10%). In contrast, Mersie et al. (1999a) reported that soils established for 8 mo with switchgrass contributed to preferential transport of atrazine compared with nonvegetated soil. They suggested that one growing season may not be sufficient time for switchgrass roots to provide additional surface area or OM (or both) to affect the sorption of atrazine. Combined, these data indicate that although nonionic or weakly basic herbicides (or both) may be detected beneath VFS, the potential for leaching is reduced in VFS soil compared with adjacent CS because of enhanced sorption, degradation, and bound residue formation. However, no study has addressed the fate of ionic herbicides or herbicide metabolites (or both) in VFS. It is likely that the leaching of ionic herbicides beneath VFS may be equal to or even greater than that of adjacent CS because of greater preferential flow in the former.

Conclusions and Recommendations

The retention of herbicide runoff by VFS has been evaluated in natural rainfall, simulated rainfall, and simulated run-on experiments. These approaches differ in scale, control of experimental variables, and ability to emulate processes that occur at the watershed scale. Data generated from highly controlled simulated run-on experiments appear to be well suited for model development, whereas data generated from natural rainfall and simulated rainfall experiments may be better suited for model verification. Thus, all three approaches are needed because they work in concert to elucidate the retention of herbicides by VFS.

Existing data unequivocally indicate the potential for VFS to reduce the transport of herbicides from source areas. However, the majority of experiments have been conducted on plots less than or equal to the field scale whereby researchers observed a reduction in herbicide load exiting the VFS relative to a plot void of a filter strip or compared to the load entering the VFS. No study has documented a decline in the concentration of herbicides in receiving water bodies in response to the installation of filter strips at the watershed scale. It is imperative that future research addresses this research gap.

The retention of herbicides as a function of VFS width depends largely on the properties of the herbicide evaluated. The relationship between the retention of strongly sorbed herbicides and VFS width is nonlinear with substantial retention occurring in the first few meters but curtailing sharply as width increases beyond approximately 5 m. Moreover, the retention of strongly sorbed compounds is correlated with sediment size, increasing in the order of clay < silt < sand. These data indicate that herbicides transported on the fine silt and clay fraction will be retained to a lesser degree than compounds transported on the sand fraction. In contrast, there is a positive correlation between the retention of moderately sorbed herbicides and VFS width. It appears that the retention of moderately sorbed herbicides is enhanced as VFS width increases because of a greater opportunity for sorption and infiltration. However, the installation of excessively wide VFS for the retention of moderately sorbed herbicides is curtailed by the willingness of the landowner to place cultivated land into VFS.

Theoretically, we have a sound understanding of the effect of area ratio on VFS efficacy. One expects VFS efficacy to decrease as the area ratio increases because of greater runoff volume, runoff rate, and herbicide loading at wider area ratios. However, our current understating of VFS efficacy as a function of area ratio is limited to extreme conditions, either inundation of the VFS where efficacy is severely compromised or total infiltration resulting in complete retention of herbicides. Future studies must adequately control experimental error associated with infiltration variability and elucidate the sorption of moderately sorbed herbicides to VFS sorbents during nonequilibrium conditions.

The type of vegetation established in VFS is expected to affect herbicide retention because of differences in their ability to promote sedimentation, infiltration, and sorption to leaves, stems, and thatch. However, only two studies have evaluated herbicide retention as a function of vegetation established in the VFS, and no differences were noted among species. Yet, differences in the ability of vegetation to promote sedimentation, infiltration, and sorption have been reported in the literature. Future studies should screen potential plant species for establishment in VFS based on their ability to tolerate herbicides used in the source areas weed control program, physically reduce surface runoff, promote infiltration and other factors impacting soil quality (i.e., OM accumulation, aggregate stability, bulk density, etc.), and enhance sorption of herbicides to leaves, stems, and thatch.

If properly maintained, older, more established VFS may be more efficacious than younger, newly established VFS because of better aggregate stability, porosity, and infiltration in the former. However, the deposition of sediment at the cultivated field–VFS interface and within the VFS proper is reported to decrease VFS efficacy over time. Thus, the VFS must be properly maintained and used in conjunction with BMP that reduce off-site transport of sediment and potentially herbicides (i.e., conservation tillage practices, contour buffers, grass hedges, grassed waterways, cover crops). Currently there is a need to evaluate herbicide retention at the watershed, field, and mesoplot scale using a systems approach, which incorporates various in-field BMP with filter strips, vegetated ditches, and wetlands.

There is a direct correlation between nominal inflow concentration and the retention of herbicides transported in the dissolved phase of surface runoff. Consequently, at higher inflow concentrations, the probability of herbicide–sorbent contact increases resulting in greater retention by a sorption mechanism. This is significant in that it may be invalid to compare the retention of different herbicides by VFS when their nominal inflow concentration cannot be controlled (i.e., experiments whereby herbicide is applied to a source area).

There are obvious differences between the retention of strongly and moderately sorbed herbicides by VFS. Because of the ability of the VFS to promote sedimentation, the retention of strongly sorbed herbicides by VFS exceeds that of moderately sorbed herbicides. Among the moderately sorbed herbicides, VFS appear to retain hydrophobic herbicides with a low water solubility to a greater degree than ionic herbicides with a high water solubility. This indicates that hydrophobic herbicides are more likely to be retained by a sorption mechanism compared with ionic or hydrophilic herbicides (or both). Future studies should be designed to address the potential differences in the sorption of moderately sorbed herbicides by VFS constituents using simulated run-on.

Enhanced sorption of nonionic and weakly basic herbicides is reported for VFS soil compared with adjacent CS. Because sorption of herbicides is inversely correlated with mobility, data indicate that the mobility of nonionic and weakly basic herbicides will be reduced in VFS. Exceptions may include ionic herbicides whose sorption to soil constituents is controlled by factors other than OM.

Generally, microbial numbers, microbial activity, and soil enzymatic activity are higher in VFS soil compared with adjacent CS. The implication is that higher microbial numbers and activity in VFS soil indicates potential for enhanced degradation of herbicides. In most instances, researchers have reported enhanced degradation of herbicides in VFS soil compared with adjacent CS. However, enhanced degradation of herbicides in VFS may depend on source area management practices (i.e., conservation tillage practices, cover crops, weed control program, rotations, etc.), time after establishment of the VFS, species established in the VFS, and herbicide properties. In particular, it is imperative that future experiments screen potential species established in VFS for the ability to enhance herbicide degradation through a rhizosphere effect.

The uptake of herbicides by species established in VFS has not been reported in the literature. Future studies should screen potential species for establishment in VFS for the ability to uptake and degrade herbicides used in the source areas weed control program. The implication is that species capable of absorbing and metabolizing herbicides in the VFS will reduce the potential for their subsequent transport to groundwater.

Researchers have expressed concern over the potential for the leaching of herbicides to ground water because enhanced infiltration in the VFS is the primary retention mechanism for moderately sorbed compounds. Moderately sorbed herbicides have been detected in shallow groundwater beneath VFS, and greater macropore flow has been reported for VFS soil compared with adjacent CS. However, comparative studies indicate that the leaching of nonionic and weakly basic herbicides is lower in VFS soil compared with adjacent CS because of enhanced sorption, degradation, and bound residue formation in the former. Future studies should address the potential for leaching of various herbicides, particularly ionic species, in VFS soil and adjacent CS.

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